MACROECONOMIC MODELS AND THE ECOSYSTEM

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ECOLOGICAL & ENVIRONMENTAL ECONOMICS

- Ecological Economics (EcoE) is an *interdisciplinary field* focused on the relationship between ecological systems and economic activities.
- EcoE emphasises limits to (physical) growth and the need for a balanced interaction between the economy and the environment.
- Environmental economics (EnvE) is a *sub-field of economics* that studies the economic impacts of environmental policies.
- EnvE integrates environmental concerns into market-based models.
- EcoE questions conventional economic wisdom, whereas EnvE uses the same 'neoclassical' conceptual frameworks (externalities, cost-benefit analysis).

THE PIONEERS

- Frederick Soddy (1877-1956) criticised the belief of the economy as a perpetual motion machine, drawing attention to the physical limits.
- Nicholas Georgescu-Roegen (1906-1994) emphasised the entropy law and the limits to economic growth.
- Karl William Kapp (1910-1976) highlighted the social and environmental costs of industrialisation.
- Kenneth Boulding (1910-1993) introduced the concept of 'Spaceship Earth' and advocated for a closed-loop economy.
- Elinor Ostrom (1933-2012) analysed the governance of common-pool resources.
- Herman Daly (1938-2022) developed ideas on steady-state economics (pioneered by the Classical Political Economists).

INTEGRATED ASSESSMENT MODELS (IAMs)

- IAMs are formal models that combine economic, environmental, and social factors.
- They assess the interactions between economic growth and environmental sustainability.
- IAMs are used for studying climate policy impacts and include 'cost-benefit analysis (CBA)' models such as DICE, FUND, and PAGE.
- CBA-IAMs are designed to estimate costs and benefits of climate policies.

THE DICE MODEL

- The DICE model (Dynamic Integrated model of Climate and the Economy) was developed by William Nordhaus in the early 1990s (Nordhaus, 1992).
- It is a CBA-IAM that evaluates the economic impacts of climate change and the costs of climate policies.
- In formal terms, it is a Ramsey growth model *plus* a damage function, an abatement function, and other equations that link GDP with CO_2 and temperature.
- It is used to derive various warming pathways. The optimum one is a temperature rise of 4-degree Celsius by 2150 (damage = 15$ trillion, abatement cost = 3$ trillion).
- Policy implications: a tax on carbon emissions is necessary to internalise the external effects of climate change.

A SIMPLIFIED DICE MODEL

- A simplified DICE model structure (in discrete time) includes:
  1) Production function: $Y_t = A_t \cdot K_{t-1}^{\alpha} \cdot N^{(1-\alpha)}$
  2) Technical progress: $A_t = A_{t-1} \cdot (1 + g_t)$, with: $g_t = g_{t-1} \cdot (1 - g_\tau)$
  3) Capital stock: $K_t = K_{t-1} \cdot (1 - \delta) + I_t$
  4) Investment: $I_t = Y_t^{net} - C_t$
  5) Emissions function: $E_t = \sigma_t \cdot Y_t^{net} \cdot (1 - \mu_t)$, with: $\sigma_t = \sigma_{t-1} \cdot (1 - g_\sigma)$
  6) Carbon concentration: $co2_t = co2_{t-1} + E_t - \phi \cdot co2_{t-1}$
  7) Temperature equation: $T_t = T_{t-1} + \lambda_t \cdot F_t$
  8) Radiative forcing: $F_t = \zeta \cdot \ln\left(\frac{co2_t}{co2_{pre}}\right)$
  9) Damage function: $d_t = \theta_1 \cdot T_{t-1} + \theta_2 \cdot T_{t-1}^2$

A SIMPLIFIED DICE MODEL (CONT'D)

9) Effective output: $Y_t^{net} = Y_t \cdot \left(1 - d_t - c_t^{mit}\right)$

10) Mitigation costs: $c_t^{mit} = \psi \cdot \mu_t^{\beta} \cdot Y_t$

11) Consumption function: $C_t = \alpha_0 + \alpha_1 \cdot Y_{t-1}^{net}$

12) Utility function: $U = \frac{C_t^{(1-\eta)} - 1}{1-\eta}$

13) Welfare: $W = \sum_{t=0}^{T} \frac{U(C_t)}{(1+\rho)^t}$

The DICE model maximises W by adjusting the control variables (such as the mitigation rate or the carbon tax rate) to determine an 'optimal' path for emissions and temperature.

Governments must raise the price of CO_2 emissions, using target carbon prices and penalty tariffs (for those who do not join the 'Climate Club').

FIG. 1 BASELINE SCENARIO (SIMPLIFIED MODEL)

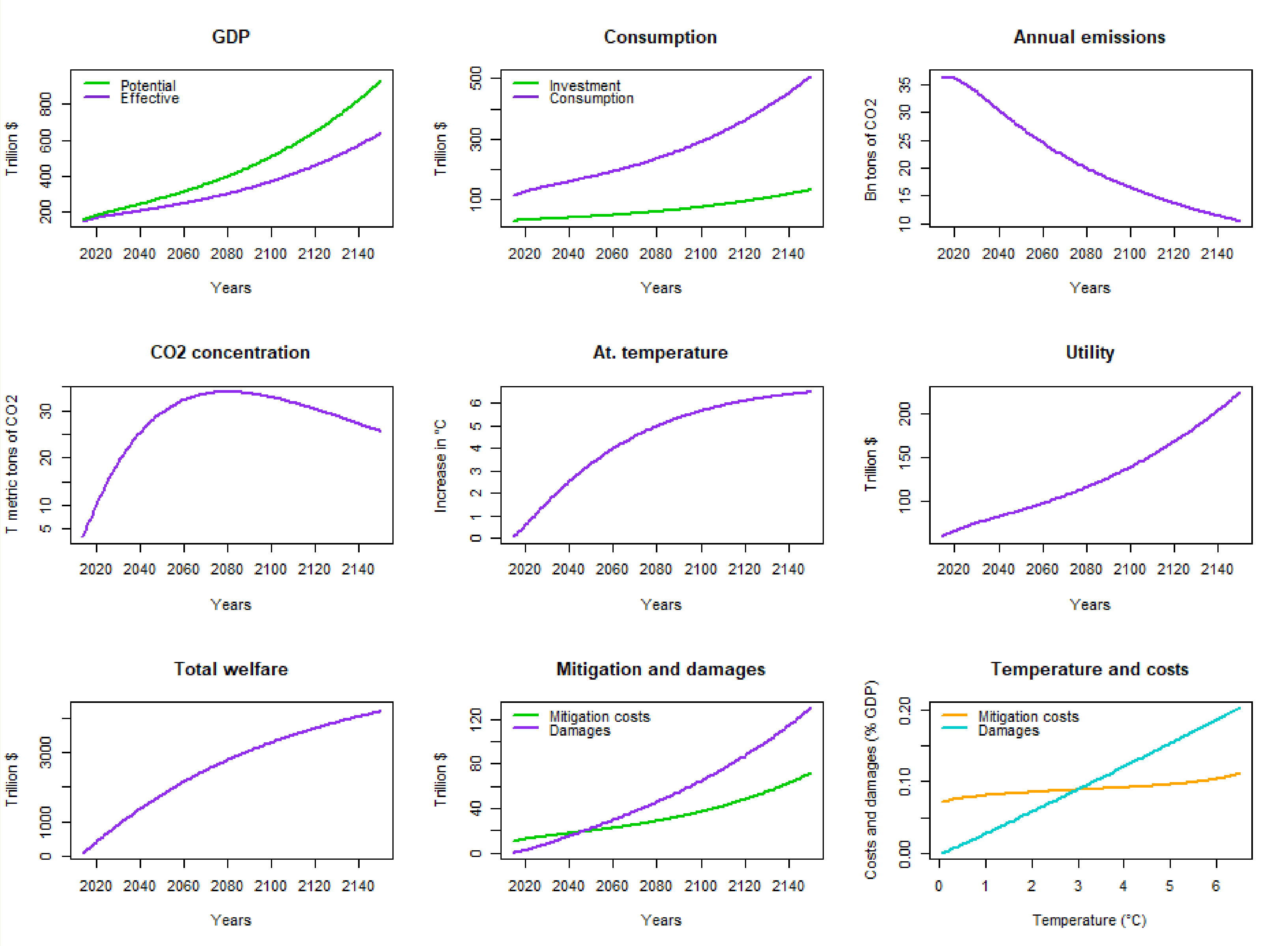


FIG. 2 ALTERNATIVE POLICIES (SIMPLIFIED MODEL)

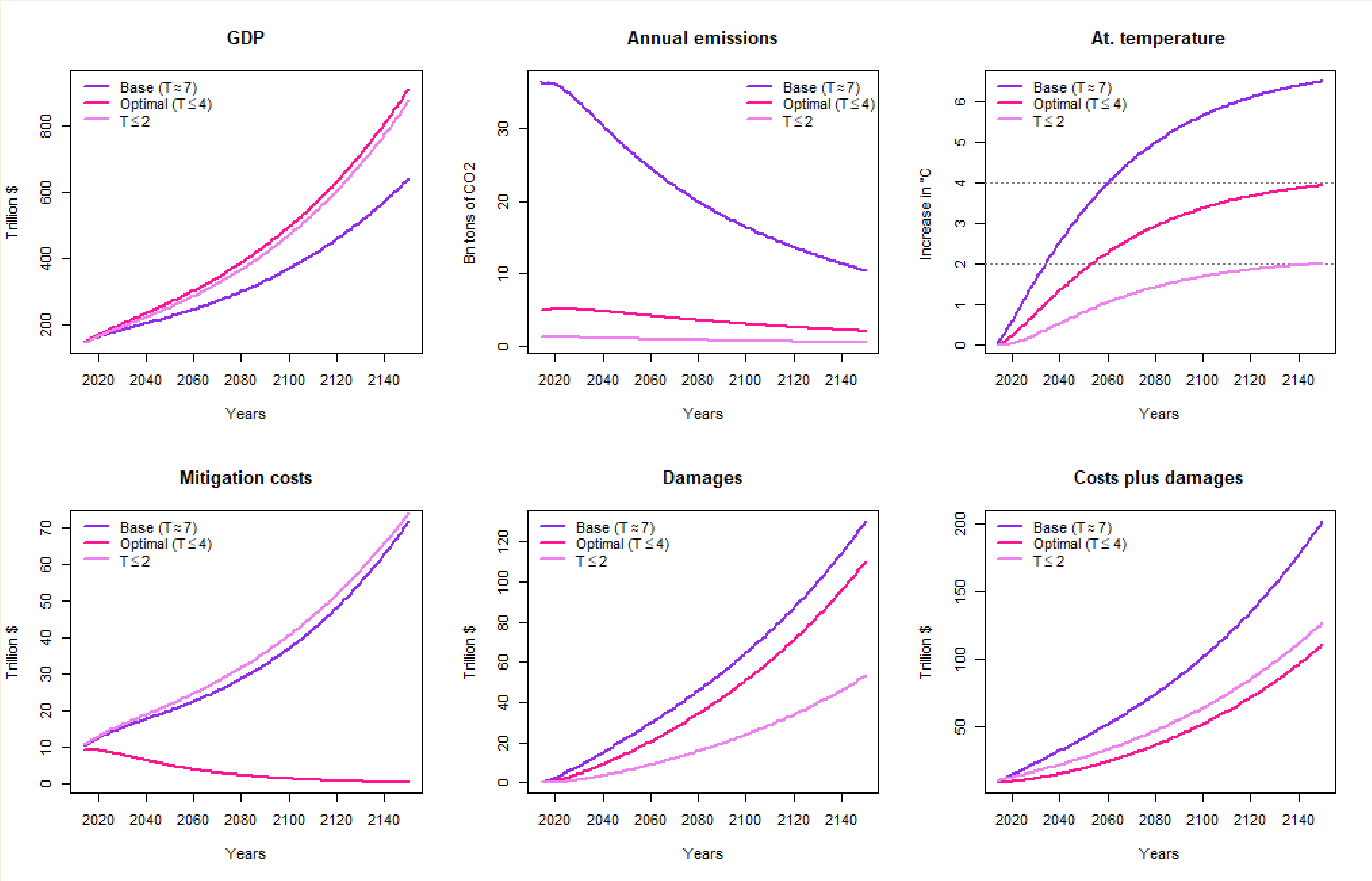
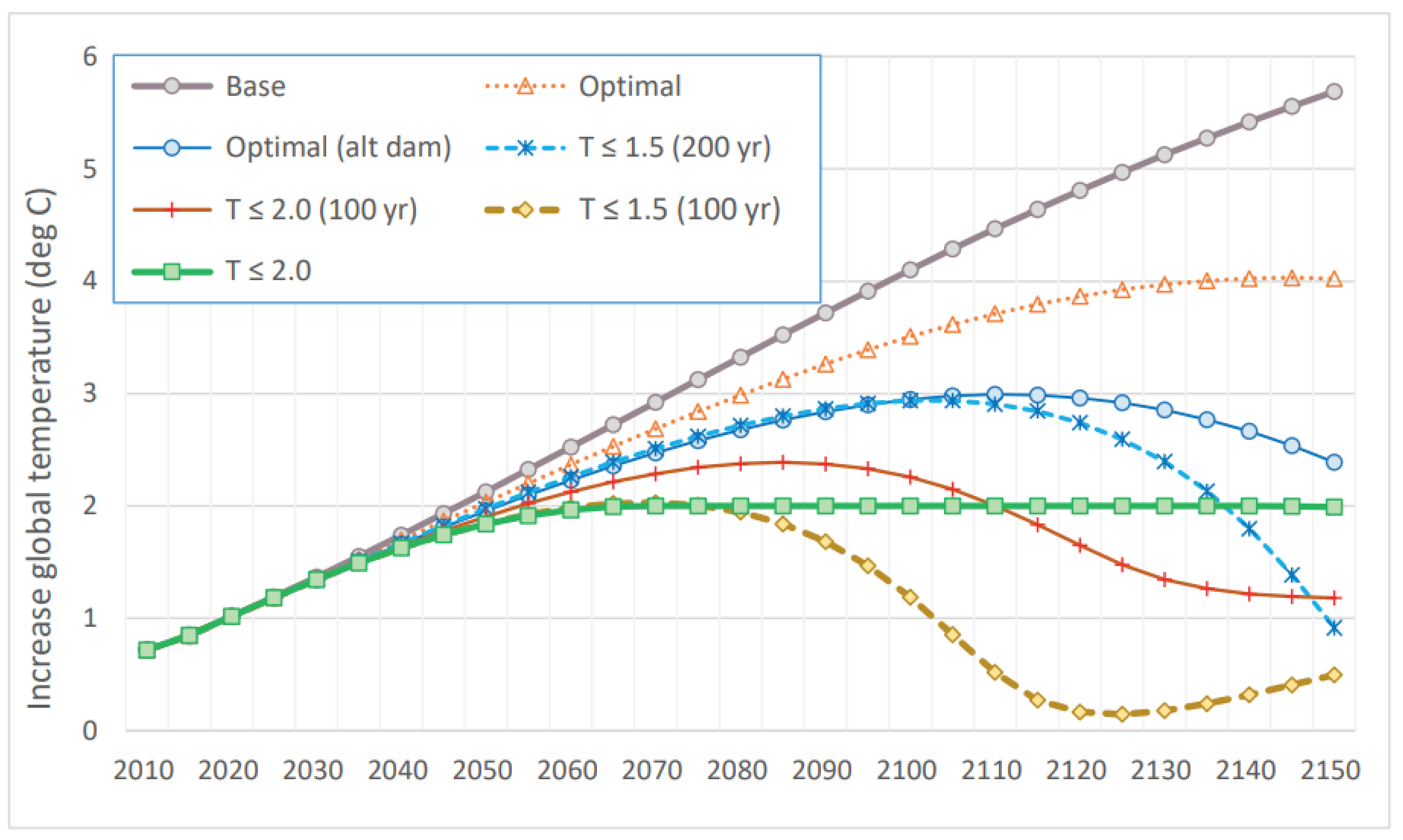
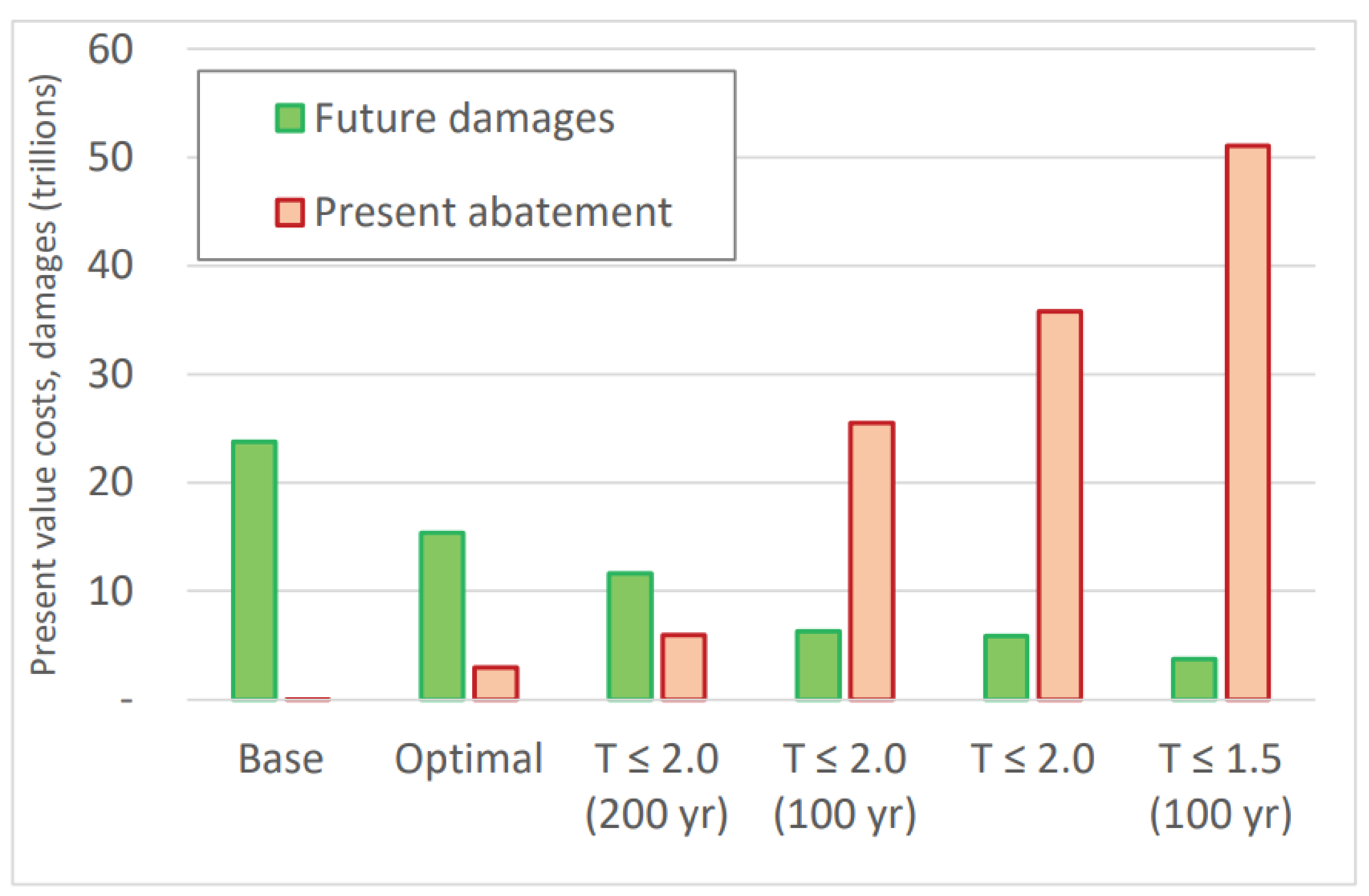


FIG. 3 TEMPERATURE TRAJECTORIES (ORIGINAL MODEL)



Source: Nordhaus, Nobel Lecture Speach, December 8, 2018

FIG. 4 ABATEMENT AND DAMAGES (ORIGINAL MODEL)



Source: Nordhaus, Nobel Lecture Speach, December 8, 2018

LIMITATIONS OF THE DICE MODEL

- The DICE model has notable limitations (e.g. Keen, 2020) including:
  - Assumes a global, uniform policy response.
  - No room for money and financial sector.
  - Limited focus on social and equity aspects of climate change.
  - Simplified representation of climate feedback mechanisms.
  - Highly sensitive to initial assumptions and discount rate.
  - Assumes that 87% of the economy will be unaffected by climate change.
  - May underestimate extreme climate risks and uncertainties.
  - No room for non-linearities, lock-in effects, tipping points, irreversibility, rebound effects, multiple equilibria, etc.

IS THERE AN ALTERNATIVE?

- Yes, there are 3 alternative methods.
- Leontief Input-Output (IO) models
  - Pros: several variables, cross-industry interdependencies, no pre-defined optimal equilibrium (unlike CGE, DSGE and neoclassical growth model).
  - Cons: static, poor financial side.
- Stock-Flow Consistent (SFC) models
  - Pros: dynamic, no pre-defined optimal equilibrium, national accounting, money and finance, entropy.
  - Cons: homogeneous output, large scale, calibration.
- Heterogenous Interacting Agent-Based (HIAB) models
  - Pros: dynamic, no pre-defined optimal equilibrium, complexity.
  - Cons: black box, mainly moment matching.

ECO IO-SFC MODELS

- Although the origins of ecological macroeconomics can be traced back to the inception of economics itself, early SFC models for economic research did not incorporate the ecosystem.
- This gap was bridged in the late 2010s (Dafermos, Nikolaidi, and Galanis, 2017, 2018; Jackson and Victor, 2015). The primary characteristic of ECO-SFC-Ms is their integration of monetary variables (following Godley and Lavoie, 2007) with physical variables (in line with Georgescu-Roegen, 1971) in a consistent manner. Several ECO-SFC models have been developed since then.
- In contrast, there are currently only a few prototypes of IO-SFC-Ms, despite some progress made in recent years (Berg, Hartley, and Richters, 2015; Jackson and Jackson, 2021, 2023; Valdecantos, 2023, Veronese Passarella, 2023).
- However, this step is essential for analysing the interaction of the ecosystem with the economy (Hardt and O'Neill, 2017) and technical progress (Veronese Passarella, 2023).

ASSUMPTIONS OF MODEL ECO-IO-PC

- The economic section is based on chapter 4 of Godley and Lavoie (2007). PC stands for portfolio choice, because households can hold their wealth in terms of cash and/or government bills.
- Key 'economic' assumptions are as follows:
  - Closed economy
  - Four agents: households, 'firms', government, central bank
  - Two financial assets: government bills and outside money (cash)
  - Fixed prices and zero net profits
  - No banks, no inside money (bank deposits)
  - Two industries
  - Circulating capital only (no inventories, no fixed capital)
  - Fixed technical coefficients
  - 1 industry = 1 technique = 1 product
  - Exogenous composition of consumption and government spending

THE ECOSYSTEM

- The ecosystem is modelled as follows:
  - 2 types of reserves: matter and energy
  - 2 types of energy: renewable and non-renewable
  - Resources are converted into reserves at a certain rate
  - Industrial CO_2 emissions result from the use of non-renewable energy
  - Atmospheric temperature is a growing function of CO_2 emissions
  - Both goods can be durable or non-durable
  - A share of durable goods is discarded in every period
  - Both waste and emissions are produced only by the firm sector

TAB. 1 THE BALANCE-SHEET

	Households	Firms (production)	Central Bank	Government	Σ
Money (cash)	$+H_h$		$-H_s$		0
Bills	$+B_h$		$+B_{cb}$	$-B_s$	0
Balance (net worth)	$-V_h$			$+V_g$	0
Σ	0	0	0	0	0

Notes: A '+' before a magnitude denotes an asset; a '–' denotes a liability.

TAB. 2 THE TRANSACTIONS-FLOW MATRIX

	Households	Firms (production)	Banks	Central Bank	Government	Σ
Consumption	$-C$	$+C$				0
Gov. spending		$+G$			$-G$	0
Income=GDP	$+Y$	$-Y$				0
Mitigation costs	$-C^{mit}$				$+C^{mit}$	0
Interest payments	$+r_{-1} \cdot B_{h,-1}$			$+r_{-1} \cdot B_{cb,-1}$	$-r_{-1} \cdot B_{s,-1}$	0
CB profits				$-r_{-1} \cdot B_{cb,-1}$	$+r_{-1} \cdot B_{cb,-1}$	0
Taxes	$-Tax$				$+Tax$	0
Δ in cash	$-\Delta H_h$			$+\Delta H_s$		0
Δ in bills	$-\Delta B_h$			$-\Delta B_{cb}$	$+\Delta B_s$	0
Σ	0	0	0	0	0	0

Notes: A '+' before a magnitude denotes a receipt or a source of funds; a '–' denotes a payment or a use of funds

TAB. 3 THE INPUT-OUTPUT STRUCTURE

		Demand for inputs		Final demand	Output
		Industry 1	Industry 2		
Production	Industry 1	$p_1 \cdot a_{11} \cdot x_1$	$p_1 \cdot a_{12} \cdot x_2$	$p_1 \cdot d_1$	$p_1 \cdot x_1$
	Industry 2	$p_2 \cdot a_{21} \cdot x_1$	$p_2 \cdot a_{22} \cdot x_2$	$p_2 \cdot d_2$	$p_2 \cdot x_2$
Value added		$p_1 \cdot x_1 - (p_1 \cdot a_{11} \cdot x_1 + p_2 \cdot a_{21}$	$p_2 \cdot x_2 - (p_2 \cdot a_{12} \cdot x_2 + p_2 \cdot a_{22}$	$\mathbf{p}^{\mathrm{T}} \cdot \mathbf{d} = Y$	
Output		$p_1 \cdot x_1$	$p_2 \cdot x_2$		$\mathbf{p}^{\mathrm{T}} \cdot \mathbf{x}$

TAB. 3 THE PHYSICAL FLOW MATRIX

	Natural reserves	
	Matter (Gt)	Energy (EJ)
Inputs		
Extracted matter	$+mat$	
Recycled socio-economic stock	$+rec$	
Renewable energy		$+ren$
Non-renewable energy	$+cen$	$+nen$
Oxygen	$+o2$	
Outputs		
Industrial CO_2 emissions	$-emis$	
Discarded socio-economic stock	$-dis$	
Dissipated energy		$-en$
Change in socio-economic stock	$-\Delta k_h$	
Total	0	0

TAB. 3 THE PHYSICAL STOCK-FLOW MATRIX

	Material reserves	Energy reserves	CO_2 concentration	Socio-economic stock
Initial stock	$k_{m,-1}$	$k_{e,-1}$	$CO2_{-1}$	$k_{h,-1}$
Resources converted into reserves	$+conv_m$	$+conv_e$		
CO_2 emissions			$+emis$	
Production of material goods				$+x_{mat}$
Extraction of matter / use of energy	$-mat$	$-en$		
Destruction of socio-economic stock				$-dis$
Final stock	k_m	k_e	$CO2$	k_h

MODEL EQUATIONS

- Macroeconomic equations of Model ECO-IO-SFC
  1) Disposable income: $YD_t = Y_t - Tax_t + r_{t-1} \cdot B_{h,t-1} - C_t^{mit}$
  2) Net tax revenue: $Tax_t = \theta \cdot \left(Y_t + r_{t-1} \cdot B_{h,t-1}\right)$
  3) Net wealth: $V_{h,t} = V_{h,t-1} + YD_t - C_t$
  4) Propensity to consume out of income: $\alpha_1 = \alpha_{10} - \alpha_{11} \cdot r_{t-1} - \alpha_{12} \cdot \Delta T_t$
  5) Money held by households: $H_{h,t} = V_{h,t} - B_{h,t}$
  6) Bills held by households: $B_{h,t}/V_{h,t} = \lambda_0 + \lambda_1 \cdot r_{t-1} - \lambda_2 \cdot YD_t/V_{h,t}$
  7) Supply of bills: $B_{s,t} = B_{s,t-1} + G_t - Tax_t + r_{t-1} \cdot \left(B_{s,t-1} - B_{cb,t-1}\right) - C_t^{mit}$
  8) Supply of money: $H_{s,t} = H_{s,t-1} + \Delta B_{h,t}$
  9) Interest rate: $r_t = \bar{r}$
  10) Real consumption: $c_t = \alpha_1 \cdot \left[\left(YD_t/p_{c,t}\right) - \epsilon_t\right] + \alpha_2 \cdot \left(V_{t-1}/p_{c,t-1}\right)$

  where: $\epsilon_t = \pi_t \cdot \frac{V_{h,t-1}}{p_{c,t}}$

MODEL EQUATIONS (CONT'D)

- Input-output equations
  - 11) Real demands: $\mathbf{d}_t = \boldsymbol{\beta}_c \cdot c_t + \boldsymbol{\beta}_g \cdot g_t$
  - 12) Real gross outputs: $\mathbf{x}_t = \mathbf{A} \cdot \mathbf{x}_t + \mathbf{d}_t$
  - 13) National income: $Y_t = \mathbf{p}_t^T \cdot \mathbf{d}_t$
  - 14) Prices of production: $\mathbf{p}_t = (w/\mathbf{pr}_t) + (\mathbf{p}_t^T \cdot \mathbf{A}) \cdot (1+m) \cdot (1+d_t)$
  - 15) Average consumer price: $p_{c,t} = \mathbf{p}_t^T \cdot \boldsymbol{\beta}_c$
  - 16) Average price for the government: $p_{g,t} = \mathbf{p}_t^T \cdot \boldsymbol{\beta}_g$
- Ecological equations
  - 17) Matter content of goods: $x_{mat,t} = \boldsymbol{\mu}_{mat}^T \cdot \mathbf{x}_t$
  - 18) Matter extraction $mat_t = x_{mat,t} - rec_t$
  - 19) Recycled matter: $rec_t = \rho_{dis} \cdot dis_t$
  - 20) Discarded socio-economic stock: $dis_t = \boldsymbol{\mu}_{mat}^T \cdot (\boldsymbol{\zeta}_{dc} \odot \mathbf{dc}_{t-1})$

MODEL EQUATIONS (CONT'D)

21) Stock of durable goods: $\mathbf{dc}_t = \mathbf{dc}_{t-1} + \boldsymbol{\beta}_c \cdot c_t - \zeta_{dc} \cdot \mathbf{dc}_{t-1}$

22) Socioeconomic stock: $k_{h,t} = k_{h,t-1} + x_{mat,t} - dis_t$

23) Waste: $wa_t = mat_t - \Delta k_{h,t}$

24) Total energy required for production: $en_t = \boldsymbol{\varepsilon}_{en}^T \cdot \mathbf{x}_t$

25) Renewable energy: $ren_t = \boldsymbol{\varepsilon}_{en}^T \cdot (\mathbf{a}_{en} \odot \mathbf{x}_t)$

26) Non-renewable energy: $nen_t = en_t - ren_t$

27) CO_2 emissions: $emis_t = \beta_e \cdot nen_t \cdot (1 - \mu)$

28) Cumulative emissions: $co2_t = co2_t + emis_t$

29) Atmosperic temperature: $T_t = [1/(1 - fnc)] \cdot tcre \cdot co2_t$

30) Matter reserves: $k_{m,t} = k_{m,t-1} + conv_{m,t} - mat_t$

31) Matter resources converted into reserves: $conv_{m,t} = \sigma_m \cdot res_{m,t}$

32) Matter resources: $res_{m,t} = res_{m,t-1} - conv_{m,t}$

33) Carbon mass of non-renewable energy: $cen_t = emis_t/car$

MODEL EQUATIONS (CONT'D)

34) Mass of oxygen: $o2_t = emis_t - cen_t$

35) Energy reserves: $k_{e,t} = k_{e,t-1} + conv_{e,t} - en_t$

36) Energy resources converted into reserves: $conv_{e,t} = \sigma_e \cdot res_{e,t}$

37) Energy resources: $res_{e,t} = res_{e,t-1} - conv_{e,t}$

38) Mitigation costs: $C_t^{mit} = \psi \cdot \mu^{\beta} \cdot Y_t$

39) Damage function: $d_t = \theta_1 \cdot T_{t-1} + \theta_2 \cdot T_{t-1}^2$

- Note: some ecological equations (emissions, carbon concentration, temperature and damages) resemble those used by the DICE model.
- The main difference is the absence of a pre-defined optimal equilibrium driving model dynamics, which is only anchored by the stock-flow consistency requirements.
- The complete list of model equations of ECO-IO-PC and the related description are available here.

FIG. 5 A SNAPSHOT OF THE TRANSACTIONS IN PERIOD t

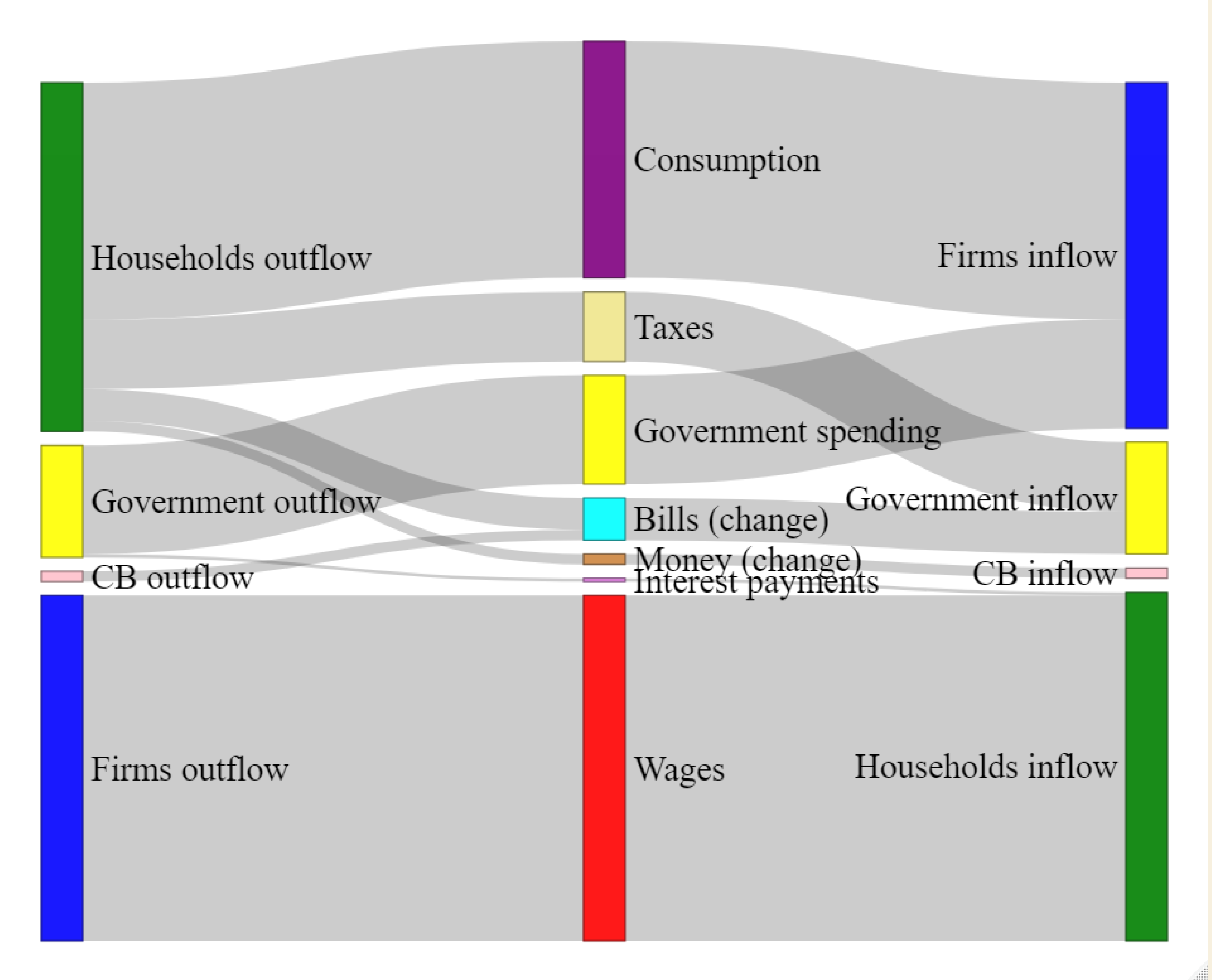


FIG. 6 CROSS-INDUSTRY INTERDEPENDENCIES IN PERIOD t

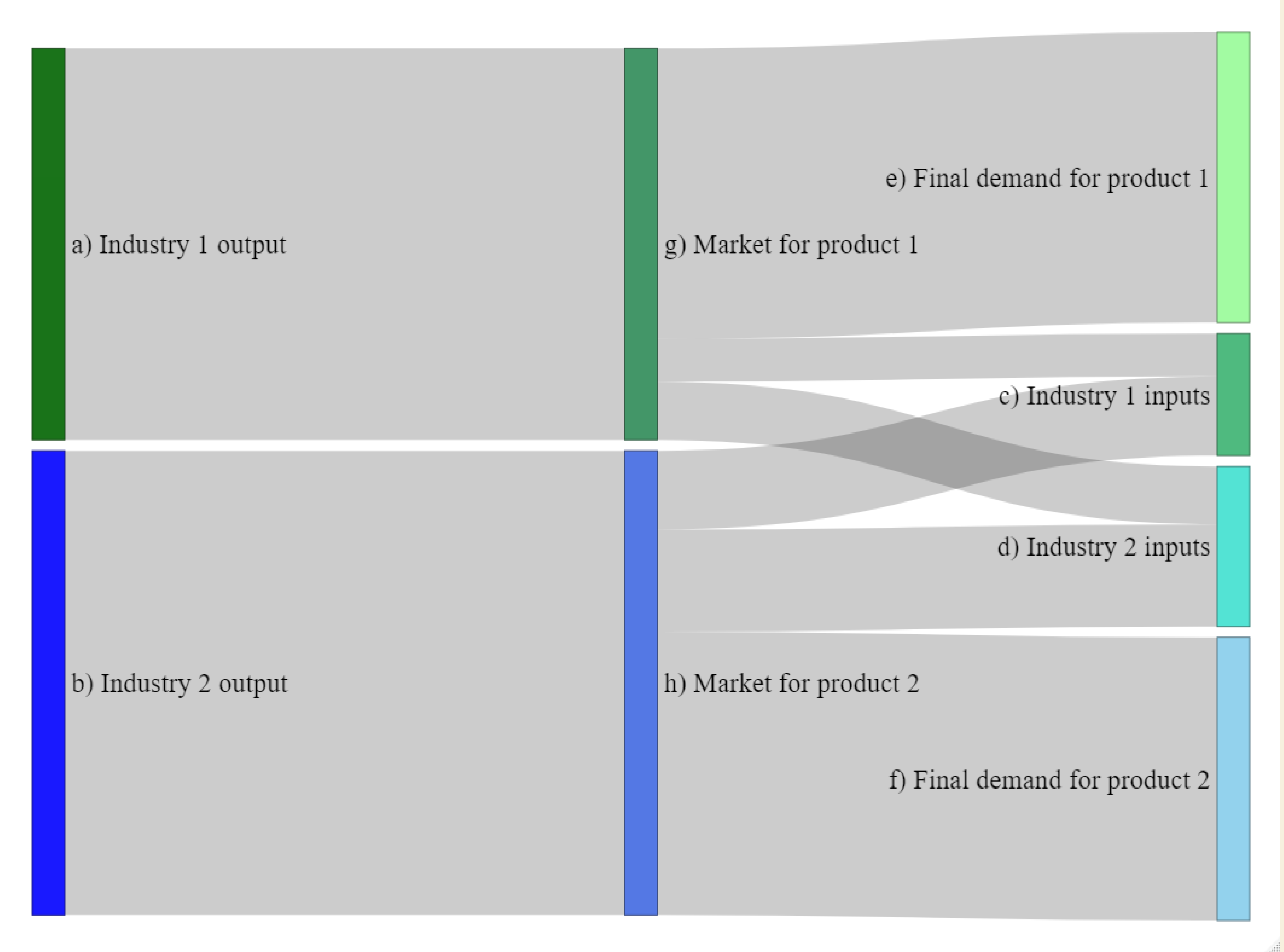
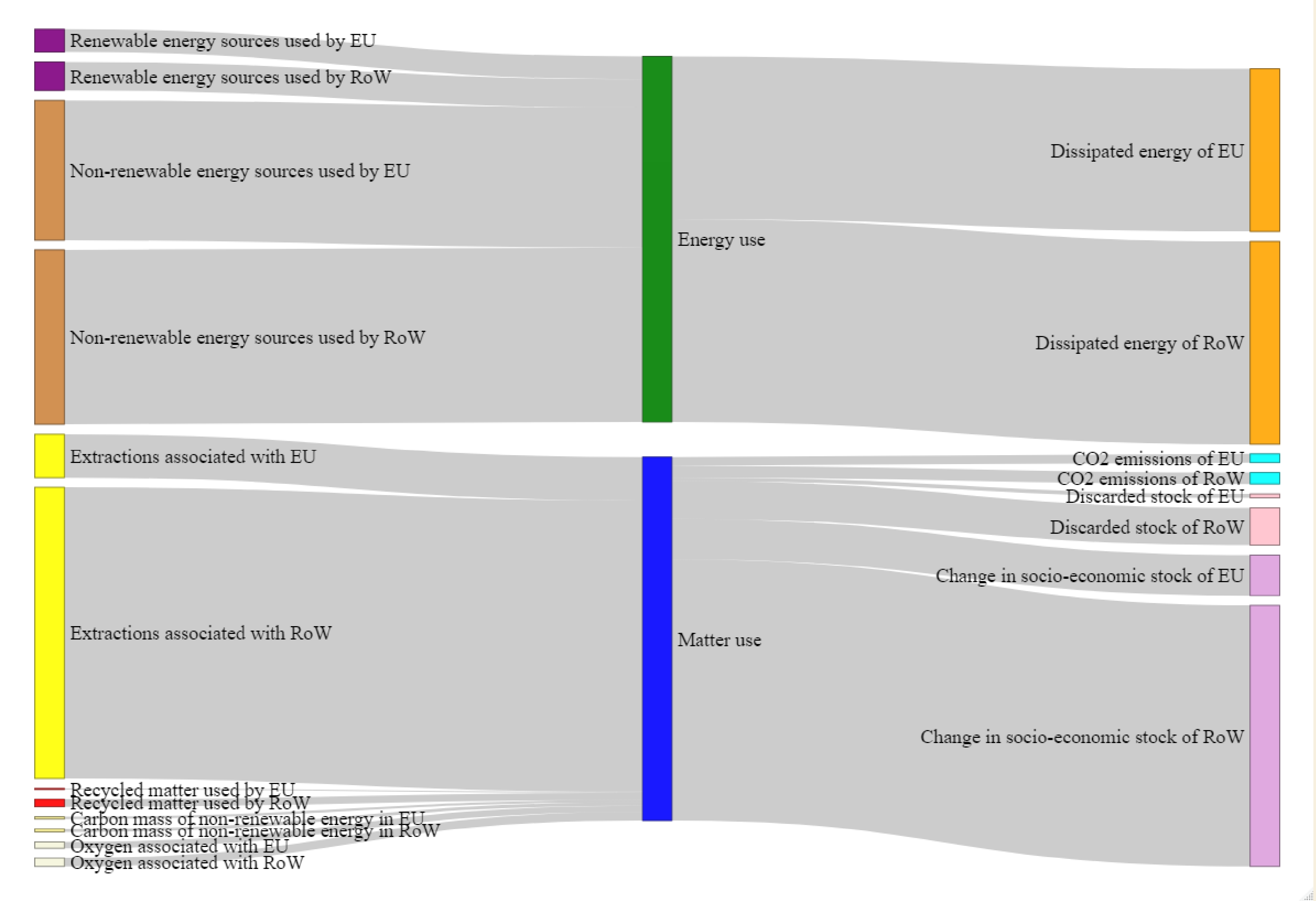
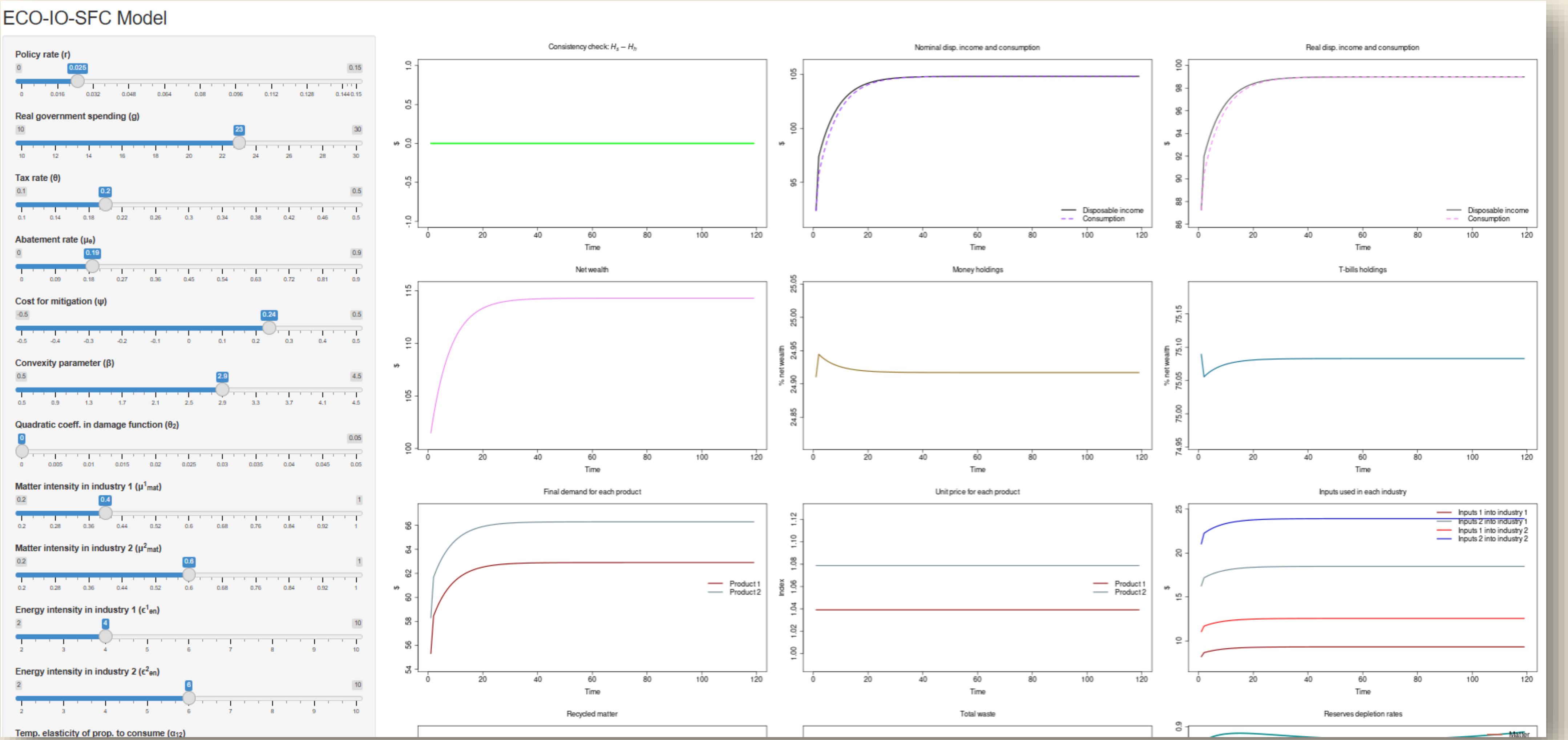


FIG. 7 ECOLOGICAL CONSTRAINTS IN PERIOD t (2 AREAS)



PLAYING WITH MODEL ECO-IO-PC



Open the interactive model

FINAL REMARKS

- CBA-IAMs are extensions of neoclassical growth models, aimed at identifying optimal pathways (welfare maximisation, cost minimisation).
- ECO-IO-SFC Ms offer an alternative approach to modelling economy-ecosystem interactions. These models do not aim to identify optimal trajectories but enable comparison of different scenarios across various dimensions.
- Main preliminary findings:
  - There is no single optimal policy for everyone.
  - Rebound effects and other unexpected outcomes are likely.
  - Effective green transition policies require interventions that support the most affected individuals, social classes, and countries.
  - Market forces alone are unlikely to achieve minimum green targets. The government must step in.

THANK YOU

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